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Finding Strongly Interacting Symmetry Breaking at the SSC

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ABSTRACT

Pairs of gauge bosons, W and Z, are a probe of the electroweak symmetry-breaking sector, since the numbers of two gauge boson events are much larger in strongly coupled models than weak. The doubly charged channels W^+W^+ and W^-W^- are cleanest, since they do not suffer from $q\bar{q}$ or gg fusion backgrounds. The like-charged gauge boson events are observable only if the symmetry breaking sector is strongly interacting.

I) INTRODUCTION

The physics program at the Superconducting Super Collider (SSC) will have have two major goals. One will be to search for new physics, for example a new gauge boson or some signal for supersymmetry. This sort of study was the subject of many of the talks at this conference. The other hope for the SSC is that it can be used to elucidate the part of the $SU(2) \times U(1)$ electroweak theory that we know little about - the symmetry breaking sector.

At present virtually the only thing we know about symmetry breaking in the standard model is that it occurs. We know that $M_W = 84$ GeV and $M_Z = 92$ GeV. We understand none of the details of the symmetry breaking sector, for example its spectrum or mass scale. We do not even know the answer to the most elemental question: Is the symmetry breaking sector strongly or weakly interacting?

In this talk I will argue that the answer to at least this last question may be within reach at the SSC. As suggested in reference [1], by looking at events $pp \rightarrow VVX$ (where $V = W$ or Z), we may be able to determine the strength of the interactions that produce symmetry breaking.

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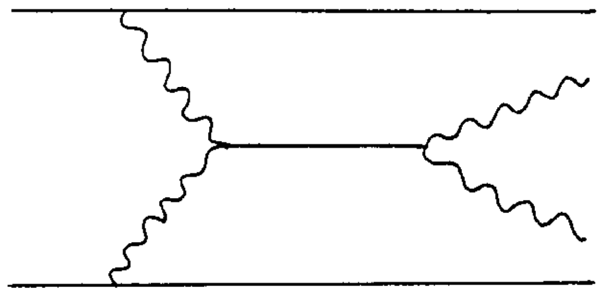
II) OBSERVATION OF THE SYMMETRY BREAKING SECTOR

That the two gauge boson events are a window into the symmetry breaking sector can be illustrated by considering the standard model (one doublet of fundamental scalars). If $m_H > 2M_Z$, the gauge boson fusion mechanism [2], figure 1, produces large numbers of Higgs bosons, and is therefore a copious source of V pairs.

Figure 1



We see that, in the standard model at least, the numbers of two gauge boson events and their typical M_{VV} are an indicator of the physics of symmetry breaking. Simple considerations show that this feature generalizes to other models as well.

Figure 2

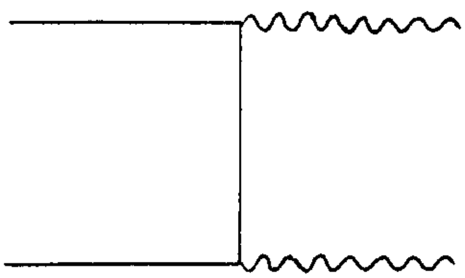
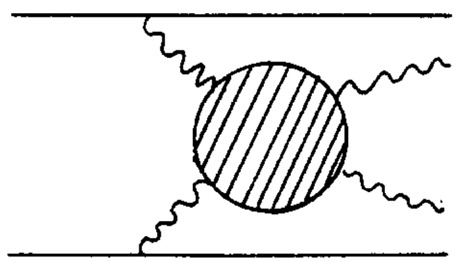


Figure 3



Figures 2 and 3 show two ways to make gauge boson pairs; figure 2 is $q\bar{q}$ annihilation, and figure 3 depicts the gauge boson fusion mechanism. Relative to $q\bar{q}$ annihilation, gauge boson fusion looks suppressed by $g^2 = .36$ (where g is the electroweak coupling constant). There is one factor of g at each of the qV vertices, common to both processes. The blob in Figure 3 is meant to represent generic $VV \rightarrow VV$ scattering, and it contains a factor of g^2. There is also some suppression due to four body vs. two body phase space.

Unfortunately, the $q\bar{q}$ annihilation process has nothing to do with symmetry breaking. (It may be interesting in its own right, as a probe of the three gauge boson vertex.) If we want gauge boson fusion to beat the background, we need the blob in Figure 2 to be large.

It will be convenient to use the Goldstone boson equivalence theorem [3] to discuss the scattering of gauge bosons. The theorem states that for energies much greater than the W mass, the amplitude $\mathcal{M}$ for any process involving an external longitudinally polarized gauge boson is equal to the amplitude for the same process with the longitudinal gauge boson replaced with the corresponding unphysical Goldstone boson:

$$\mathcal{M}(V_L(p_1), V_L(p_2), \ldots) = \mathcal{M}(\phi_V(p_1), \phi_V(p_2), \ldots)_R + O(M_W/E)$$

The right-hand side is evaluated in an R-gauge, and the $\phi_V(p_i)$ are the R-gauge Goldstone bosons associated with the longitudinal modes $V_L(p_i)$.

In the Standard Model, the self-interactions of the ϕ's are given by

$$L_{STD} = (\partial^\mu \Phi)^\dagger(\partial_\mu \Phi) - \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2}\right)^2$$

where

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}(H + v + i\phi_Z) \\ i\phi_{W+} \end{pmatrix}$$

and v is the vacuum expectation value of the H field, 250 GeV. Using the equivalence theorem to evaluate the blob in figure 3, we see that there are, in the standard model, only two ways for the rescattering to be large. The first, as in figure 1, is if the invariant mass of the final state gauge bosons is close to the mass of the Higgs boson. The other way is to have the four gauge bosons at the blob be longitudinal, and to have the interaction strength parameter, λ, be large.

In the standard model, the mass of the Higgs boson is given at tree level by $M_H^2 = 2\lambda v^2$, so taking λ large implies a heavy Higgs boson. The tree-level theory violates unitarity bounds for VV scattering if $M_H > 1$ TeV ($\lambda > 8$) [4]. Furthermore, the expansion parameter in the loop expansion is $\lambda/(4\pi^2)$, so there is no hope of calculating the standard model perturbatively unless $\lambda/(4\pi^2) \ll 1$, or $M_H^2 \ll 2.5$ TeV^2.

It is possible to calculate in this strongly interacting limit of the standard model by drawing an analogy to hadron physics. The ϕ's are the Goldstone bosons of the symmetry breaking sector; they are analogous to the pions, which are the the Goldstone bosons of the broken quark chiral symmetry. The calculation of $\phi\phi \to \phi\phi$ scattering is the same as the calculation of $\pi\pi \to \pi\pi$. This latter process was calculated many years ago by Weinberg [5]. The only inputs are the chiral

$SU(2) \times SU(2)$ current algebra of the left and right handed currents

$$[L^a, L^b] = i\epsilon^{abc} L^c$$
$$[R^a, R^b] = i\epsilon^{abc} R^c$$
$$[L^a, R^b] = 0$$

and the Partially Conserved Axial Current relation

$$\partial^\mu A^a_\mu = f_\pi m_\pi^2 \pi^a$$

where $A^a_\mu = \frac{1}{2}(L^a_\mu - R^a_\mu)$ and f_π is the pion decay constant. Chanowitz and Gaillard [1] have pointed out that since the symmetry breaking lagrangian of the standard model is the linear σ-model, which has a chiral $SU(2) \times SU(2)$ symmetry, we may directly use Weinberg's result for the amplitude for low energy pion-pion scattering:

$$\mathcal{M}(\pi^i \pi^j \to \pi^k \pi^l) = \frac{s}{f_\pi^2}\delta^{ij}\delta^{kl} + \frac{t}{f_\pi^2}\delta^{ik}\delta^{jl} + \frac{u}{f_\pi^2}\delta^{il}\delta^{jk} + O(s^2) + O(m_\pi^2)$$

The amplitude for $\phi\phi \to \phi\phi$ scattering is simply given by replacing f_π by v.

In non-standard models there may or may not be a chiral $SU(2) \times SU(2)$ symmetry, but there must be an $SU(2)_L$ invariance; it is the global version of the symmetry that is gauged. This $SU(2)$ has an associated current L^a_μ, which obeys the commutation relation given above. There need not be any $SU(2)_R$ and associated R^a_μ current.

It is, nevertheless, possible to repeat Weinberg's argument using just the left-handed current algebra. The results are *general* low energy theorems [6]

$$\mathcal{M}(\phi_+\phi_- \to \phi_Z\phi_Z) = \frac{s}{v^2\rho} + O(s^2)$$
$$\mathcal{M}(\phi_+\phi_- \to \phi_+\phi_-) = -\frac{u}{v^2}\left(4 - \frac{3}{\rho}\right) + O(s^2)$$
$$\mathcal{M}(\phi_Z\phi_Z \to \phi_Z\phi_Z) = 0 + O(s^2)$$

where

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2(\theta_W)}$$

All other processes may obtained from these by crossing. The scattering amplitudes always have these forms, *as long as there are no light ($m \sim M_W$) particles in the Higgs sector*. Since we know from experiment that $\rho = 1$, the low energy amplitudes always assume their universal form in any phenomenologically viable model.

The significance of the low energy theorems can be illustrated simply. To lowest order in s, only three partial waves of of $\phi\phi \to \phi\phi$ of definite angular momentum and isospin have non-zero scattering amplitudes: $a_{JI} = a_{00}$, a_{11}, and a_{02}. For example, the first low energy theorem above implies that, for $\rho = 1$,

$$a_{00} = \frac{s}{16\pi v^2} + O(s^2)$$

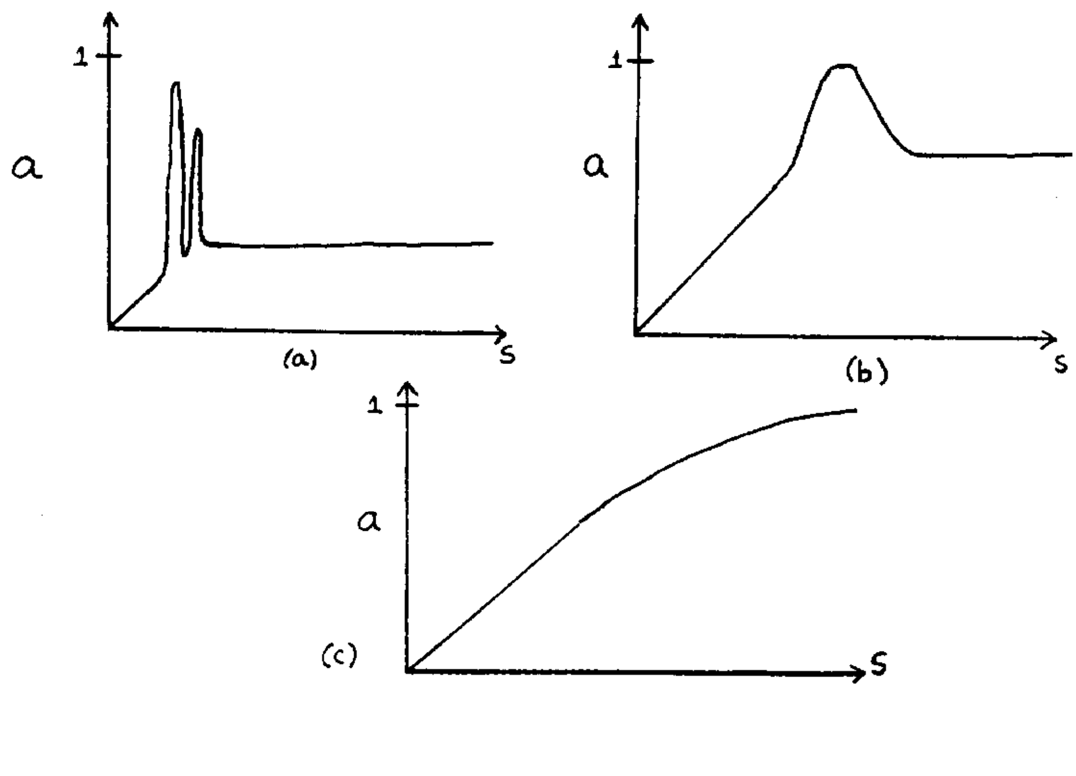
Figure 4 shows the scattering amplitude in one of these partial waves in three different hypothetical symmetry breaking sectors.

Figure 4a shows the amplitude in a generic weakly interacting model. At small s (but above M_W^2, so the equivalence theorem applies), the amplitude grows like s, with the coefficient implied by the amplitudes given above. At some mass, well below 1 TeV, there are one or more narrow resonances, which cut off the growth of the amplitude. Above this energy range, the amplitude is far from 1, the maximum value allowed by unitarity.

Figure 4b shows a strongly interacting model, for example the standard model with a Higgs boson mass of about 1 TeV. As before, the amplitude grows linearly with s at small energies, but it gets to grow much further before being cut off by a broad resonance. Above the bump the scattering amplitude is larger than in figure 4a, but below the unitarity limit.

Figure 4c shows a limiting case of a strongly interacting model. There are no resonances, the amplitude just grows until it smoothly flattens out. In the case shown, the amplitude is near the unitarity limit at large energies. It is of course a logical possibility that the amplitude flattens out at low energies, leaving the amplitude small over the entire range of s, but it is difficult to construct models that exhibit this behavior in all three partial waves at once.

Figure 4



III) EVALUATION OF THE SIGNAL RATES

One may now use this physical insight to evaluate the two gauge boson signal at a high energy collider. It is simplest to use the "effective-W" approximation [7,1]. This approximation is the analogue of the effective-photon approximation used in two-photon physics. It is a way of computing a gauge boson fusion process, as in figure 3. The diagram is computed by convoluting an effective luminosity of gauge bosons inside the proton with the cross section for on-shell $VV \rightarrow VV$ scattering.

For the gauge boson scattering blob in figure 3 one can use the amplitude $\phi\phi \rightarrow \phi\phi$ given by any model of the symmetry breaking sector. One possibility is the standard model with a Higgs boson mass of 1 TeV. One may also evaluate the model of reference [1], in which the absolute value of the amplitude for a given partial wave grows linearly with s until it reaches 1, at which point the growth stops. For example, the a_{00} partial wave is given by

$$|a_{00}| = \frac{s}{16\pi v^2}\theta\left(1 - \frac{s}{16\pi v^2}\right) + \theta\left(\frac{s}{16\pi v^2} - 1\right)$$

Yet another possibility is to use a more smoothly unitarized amplitude [8]

$$a_{00} = \frac{1}{16\pi v^2/s + i}$$

This amplitude has the advantage that it preserves elastic unitarity, staying on the Argand circle. Lastly, it is possible to simply use the data from $\pi\pi$ scattering, scaling the energies by the replacement $f_\pi \rightarrow v$. While there is no particular reason to assume that far above threshold the scattering of ϕ's looks like the scattering of π's, this procedure at least has the advantage that it is based on real world strongly interacting physics, rather than an arbitrary unitarization of a scattering amplitude.

There are a few difficulties in the use of experimental $\pi\pi \rightarrow \pi\pi$ data. First of all, there is not yet good agreement between various measurements. The situation is especially bad in the isospin two channel, which will be of interest later. The experimental situation is very nicely summarized in figure 6 of reference [9].

Another problem is that scaling the the pion mass by v/f_π would give $M_W =$ 360 GeV. In other words, the chiral $SU(2) \times SU(2)$ is a much better symmetry for the ϕ's than for pions.

Both of these difficulties may be mitigated by the use of a chiral lagrangian [10] to describe the $\pi\pi$ scattering*. To fourth order in derivatives, the chiral

*The procedure described here for scaling the experimental $\pi\pi$ data is different from that used in reference [11]. In that case, the pion mass was treated in a somewhat more *ad hoc* fashion, and below the lowest measured data point the amplitude given by the low energy theorem was used.

lagrangian for the pions is given by

$$\begin{aligned}\mathcal{L} =&\frac{f^2}{4}tr(\partial^\mu\Sigma^\dagger\partial_\mu\Sigma) + \frac{m^2f^2}{4}tr(\Sigma^\dagger + \Sigma)\\ &+\frac{\alpha_1}{4}(tr(\partial^\mu\Sigma^\dagger\partial_\mu\Sigma))^2 + \frac{\alpha_2}{4}tr(\partial^\mu\Sigma^\dagger\partial^\nu\Sigma)tr(\partial_\mu\Sigma^\dagger\partial_\nu\Sigma)\\ &+\frac{\alpha_3}{4}m_\pi^4 tr(\Sigma)tr(\Sigma^\dagger) + \frac{\alpha_4}{4}m_\pi^2 tr(\partial^\mu\Sigma^\dagger\partial_\mu\Sigma(\Sigma+\Sigma^\dagger))\end{aligned}$$

where

$$\Sigma = e^{i\pi\cdot\tau/f}$$

Calculating this lagrangian to one-loop order [12], one may fit the dimensionless coefficients α_i to the experimental data [9]†. This procedure yields amplitudes that work well below about the mass of the ρ, as shown in figure 6 of reference [9].

One may now make the replacements $f_\pi \to v$ and $m_\pi \to 0$, holding the α's fixed, which yields the required amplitudes for $\phi\phi \to \phi\phi$ scattering. Note that this procedure allows the data from the better measured channels, a_{00} and a_{11}, to tell us something about the poorly measured channel of interest, a_{02}.

The amplitudes thus obtained grow too rapidly above 1800 GeV, which is about equal to the scaled value of the ρ mass. Above about 2300 GeV they violate unitarity badly. In the numbers presented below, an *ad hoc* amplitude was used between 1800 and 3000 GeV, which joins smoothly to the maximum allowed value $|a_{02}| = 1$ at about 3000 GeV. Above this energy 1 is used for the amplitude. Since only about 1/3 of the signal comes from the region above 1800 GeV, the uncertainty thus introduced is less than about 20 percent.

IV) EVALUATION OF THE BACKGROUND RATES

It is more straightforward to calculate the background than the signal. There are three processes which contribute to production of two gauge boson final states.

The largest background (in the WZ, W^+W^- and ZZ channels) is the $q\bar{q}$ annihilation depicted in figure 2. This amplitude can be evaluated in closed form [13].

In the neutral channels there is a significant background from gluon-gluon fusion processes that produce the two gauge bosons via triangle and box diagrams. These have been evaluated [14] and are about 1/3 the size of the $q\bar{q}$ annihilation processes. In the numbers presented below, the values for the backgrounds of the charge zero channels are the $q\bar{q}$ values, increased by about 30% to account for gg fusion.

There is also a significant background from the diagrams in which a gluon is exchanged between the two quark lines, which then emit the two gauge bosons.

†The coefficients f and m in the lagrangian above are approximately but not exactly equal to f_π and m_π respectively; they receive corrections from loop effects.

This process has been evaluated only partially in the W^+W^- channel [15], and not at all for the WZ and ZZ channels. In the doubly-charged channels the disagreement between reference [11] and reference [16] has recently been resolved in favor of the latter. The distribution of the gauge bosons in this process is strongly forward peaked, since the gauge boson bremsstrahlung prefers small opening angles. This process is the leading source of background in the charge 2 channel, since the other processes are absent. In the other channels, above 1 TeV, the gluon-exchange process should be small compared to the other sources of background.

The partonic amplitudes must be convoluted with structure functions to yield real event rates. Throughout this work the EHLQ set II [17] structure functions were used.

V) OBSERVABILITY

Table 1 shows the number of signal and background events per year in the charge 0 and 1 channels at the SSC, assuming a standard SSC year of 10^{40} cm^2 at 40 TeV. For the modes shown below, the final state lepton is an e or μ when its source was a Z decay; in W decays τ's are also allowed. There is a cut forcing $y_V < 1.5$, and there is also a cut on invariant mass, as shown in the second column. The first column is the number of events given by the linear model for the amplitude of reference [1] described above. The second is the number of events in the standard model with a Higgs boson mass of 1 TeV. The third column shows the number of background events from $q\bar{q}$ and gg fusion, as described above.

Table 1

Mode		Cuts	Linear	1 TeV std.	Background
ZZ	$\to (l^+l^-)(l^+l^-)$	$M_{ZZ} > 2$ TeV	.5	0	.1
	$\to (l^+l^-)(\nu\bar{\nu})$	$2\sqrt{p_{\perp Z}^2 + M_Z^2} > 2$ TeV	3	0	.9
	$\to (l^+l^-)(l^+l^-)$	$M_{ZZ} > 1$ TeV	2	4	2
	$\to (l^+l^-)(\nu\bar{\nu})$	$2\sqrt{p_{\perp Z}^2 + M_Z^2} > 1$ TeV	17	24	10
W^+Z	$\to (l^+l^-)(l^+\nu)$	$M_{WZ} > 2$ TeV	4	0	.7
	$\to (l^+l^-)(l^+\nu)$	$M_{WZ} > 1$ TeV	11	0	10
W^+W^-	$\to (l^+\nu)(l^-\bar{\nu})$	$M_{WW} > 2$ TeV	9	2	8
	$\to (l^+\nu)(l^-\bar{\nu})$	$M_{WW} > 1$ TeV	39	140	130

Unfortunately, the use of the "gold plated" mode, $ZZ \to (l^+l^-)(l^+l^-)$ appears to be ruled out. This mode is especially useful for finding the Higgs boson if its mass is below about 600 GeV [18]. For heavier Higgs boson masses, or in the strongly coupled model above, the rates are too small to be significant above $q\bar{q}$ and gg backgrounds.

The $ZZ \to (l^+l^-)(\nu\bar{\nu})$ mode has somewhat larger rates, but it suffers from a large "garbage" background coming from $Z + jet$ events in which the jet is lost. The cuts required to remove this background may reduce the rates by as much as a factor of two [18]. Moreover, the use of this mode requires a hermetic detector, with hadronic calorimetry coverage out to a rapidity of 5.5 or so.

Note that, in all the channels above, there are more events above 2 TeV in the linear model than in the 1 TeV Higgs boson model. This illustrates the property shown in figure 4 above; above the Higgs boson resonance the standard model amplitude goes to a value less than 1, while in the linear model the amplitude remains large.

Not shown in the table above is the possibility of using the $W^+W^- \to (q\bar{q})(l\nu)$ mode. The advantage of this mode is its enormous branching ratio. The disadvantage is an overwhelming background from $W + jets$ events. However, it has recently been suggested that the multiplicity of the jets in the signal and background processes may be different, and that therefore a cut based on particle multiplicity may be able to reduce the backgrounds [19]. If this idea is useful in practice, it may make symmetry breaking physics much easier to study at the SSC.

On the other hand, if the top quark is heavier than the W, then the top decays into real W's, and the W^+W^- modes will be swamped by $t\bar{t} \to W^+bW^-\bar{b}$ events.

It has recently been noted that the absence of $q\bar{q}$ and gg backgrounds makes the the doubly charged gauge boson pair events W^+W^+ and W^+W^- an especially clean signal of strongly interacting symmetry breaking [11]. There is, unfortunately, an appreciable background from gluon exchange diagrams.

The first four columns of table 2 show the numbers of events per year from the linear model, the QCD data used as described above, and the standard model with 1 TeV and 100 GeV Higgs boson masses. The fifth column is the background from gluon exchange. A standard SSC year was assumed, and the W's are observed decays to e's or μ's (but not, as in table 1, τ's). The cuts imposed were $M_{WW} > 800$ GeV (a theorists cut, since the neutrinos are lost), $p_\perp$ of the lepton bigger than 50 GeV (to keep it far from beam jets), and $y_{\text{lepton}} < 2$.

Table 2

Mode	Linear	QCD	1 TeV std.	100GeV std.	Background
W^+W^+	18	8	2.5	0	5
W^-W^-	5.5	2.5	1	0	2

None of the numbers in the table above are overwhelming signals. If the physics of symmetry breaking is like the QCD or the 1 TeV Higgs boson mass models then the doubly charged gauge boson signal is difficult to observe. On the other hand, table 2 represents something of a worst case. If the top quark weighs more than the W then the rates above will increase by a factor of $16/9$. If τ's can be used then the numbers increase by a factor of $9/4$.

The ratio of the signal in the two channels $N(W^+W^+) : N(W^-W^-)$ is always about 3:1, because there are more u than d quarks in a proton. This may help be a check against possible "garbage" backgrounds, which come in a ratio more nearly 1:1.

There are no signal events in the 100 GeV Higgs boson mass standard model, which is weakly interacting. This agrees well with the qualitative picture presented in figure 4 above. Thus, the like-charged gauge boson pair signal is observable only if the symmetry breaking sector is strongly interacting.

VI) CONCLUSIONS

Gauge boson fusion is an appreciable source of final state gauge boson pairs if the symmetry breaking sector is strongly interacting. The "low energy" behavior of the gauge bosons scattering amplitudes is independent of the details of the symmetry breaking sector, as long it has no light scalars. If there are such scalars, then they will be produced and can possibly be studied directly.

In the charge 0 and 1 sectors, the gauge boson pair signal may be observable in purely leptonic decays over the $q\bar{q}$ and gg annihilation backgrounds. Use of q jet decay modes of the W remain an open question, and will likely be impossible if $m_{top} > M_W$.

The like-charged W channels are relatively clean and come with a built-in check, $N(W^+W^+) : N(W^-W^-)$ is 3:1.

Therefore, it may be possible at the SSC to tell strongly interacting symmetry breaking from weak.

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